Evaluation of COTS Solutions to Support Flight Operations Quality Assurance in Business/Corporate Aviation

Michael A. Bromfield[1] & Thomas Walton[2]
Institute for Future Transport & Cities, Coventry University, Gulson Street, Coventry, CV1 2JH, United Kingdom

and
David Wright[3] and Malcom Rusby[4]
Corporate Aviation Safety Executive, Redhill, Sussex, United Kingdom

Abstract

During the period 2003~ 2011 worldwide accident rates for business/corporate aviation were nearly four times that for commercial aviation. Flight Operations Quality Assurance (FOQA) or Flight Data Monitoring (FDM) - the collection of real-time flight data for continuous safety improvement - has been routinely used by commercial aviation for over 50 years. Regulatory authorities only require airplanes over 27 tonnes Maximum Take-off Weight to operate a FOQA/FDM programme. Corporate/business aviation operators generally operate airplanes less than 20 tonnes using a diverse range of airplanes which may include a single engine, twin engine, turbo-prop and/or very light jets. This study investigates the use of low-cost, independent Commercial-off-the-shelf (COTS) technologies utilising a combination of Global Positioning Systems (GPS) and Attitude Heading & Referencing Systems (AHRS) to sense and record key flight data parameters in support of a FOQA/FDM programme for corporate operators with diverse, lower weight category and legacy airplanes. The preliminary results suggest that independent COTS GPS/AHRS systems and EFIS systems (where installed) can usefully support FOQA/FDM for lower weight category and legacy airplanes.

I. Nomenclature

AHRS	=	Attitude, Heading & Referencing System
AoA	=	Angle of Attack (degrees)
CAA	=	UK Civil Aviation Authority
CAP	=	Civil Aviation Publication
CAS	=	Calibrated Airspeed (kts)
CASE	=	Corporate Aviation Safety Executive
COTS	=	Commercial Off The Shelf
CSV	=	Comma Separated Value
CVR	=	Cockpit Voice Recorder
EFIS	=	Electronic Flight Information System
FAA	=	Federal Aviation Administration
FDAU	=	Flight Data Acquisition Unit
FDM	=	Flight Data Monitoring
FDR	=	Flight Data Recorder

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[1] Senior Lecturer in Aerospace, Institute for Future Transport & Cities, Faculty of Engineering & Computing, AIAA Member
[2] Research Assistant, Institute for Future Transport & Cities, Faculty of Engineering & Computing
[3] Flight Data Monitoring Specialist, Corporate Aviation Safety Executive
[4] Flight Safety Manager, Corporate Aviation Safety Executive

FFS	=	Full Flight Simulator
FOQA	=	Flight Operations Quality Assurance (see also FDM)
FOQM	=	Flight Operations Quality Management (see also FOQA
GPS	=	Global Positioning System
GSPD	=	Groundspeed (kts)
LARS	=	Lightweight Airplane Recording System
LFL	=	Logical Frame Layout
MEMS	=	Micro-electro Mechanical System
OPC	=	Operator's Proficiency Check
PCMCIA	=	Personal Computer Memory Card International Association
QAR	=	Quick Access Recorder
SD	=	Secure Digital
SSDR	=	Solid State Data Recorder
TCAS	=	Traffic Collision Avoidance System
USB	=	Universal Serial Bus
μQAR	=	Micro Quick Access Recorder

II. Introduction

Worldwide fatal accident rates for the period 2003~ 2011 for business/corporate aviation were nearly four times that for commercial aviation [1]. The 5-year totals for accident rates from 2009~2013 by phase of flight for Business Aviation airplanes [2] shows that 19.1% of accidents for business jets take place in the take-off & climb and 66.4% in the approach & landing. Similarly 18% of accidents for turboprops occur in the take-off & climb and 64.3% in the approach & landing (Fig. 1).

FOQA/FDM - the collection of real-time flight data for continuous safety improvement - has been commonly used by commercial airlines for 50+ years [3] and more recently in rotary wing operations [4]. Currently, regulatory authorities only require airplane over 27 tonnes Maximum Take-off Weight to operate a FOQA/FDM programme (5). FOQA/FDM is recommend but not mandatory for airplanes between 20~27 tonnes and optional for lower weight categories. Corporate/business aviation operators generally utilise airplanes less than 20 tonnes using a diverse range of airplanes which may include a mix of single engine, twin engine, turbo-prop and/or very light jets. The absence of mandatory requirements, lack of FDRs and lack of digital flight instruments in legacy airplanes means that flight data is not readily available to support FOQA/FDM. Operators with modern fleets and higher weight category airplanes utilise QARs to collect flight data, these units linking directly to the airplane's Flight Data Recorder or digital data bus. These airborne DFDRs are designed to provide quick and easy access to raw flight data, using USB or cellular network connections and/or the use of standard flash memory cards. QARs typically sample 60+ flight data parameters at frequencies ranging from 0.25 (e.g. engine pressure ratios) to 8 Hz (e.g. accelerations). This study highlights key results with respect to the feasibility of using COTS technologies (LARSs) utilising a combination of GPS and AHRS to sense and record key flight data parameters in support a FOQA/FDM programme for corporate operators with diverse, lower weight category and legacy airplanes [6]. These are completely stand-alone units with built-in sensors (AHRS + GPS) capable of recording data to removable media and may use an internal or external power supply. In the USA, these devices commonly referred to as LARS maybe crash-resistant but not usually crashworthy since their primary purpose is to collect data in support of an FDM programme.

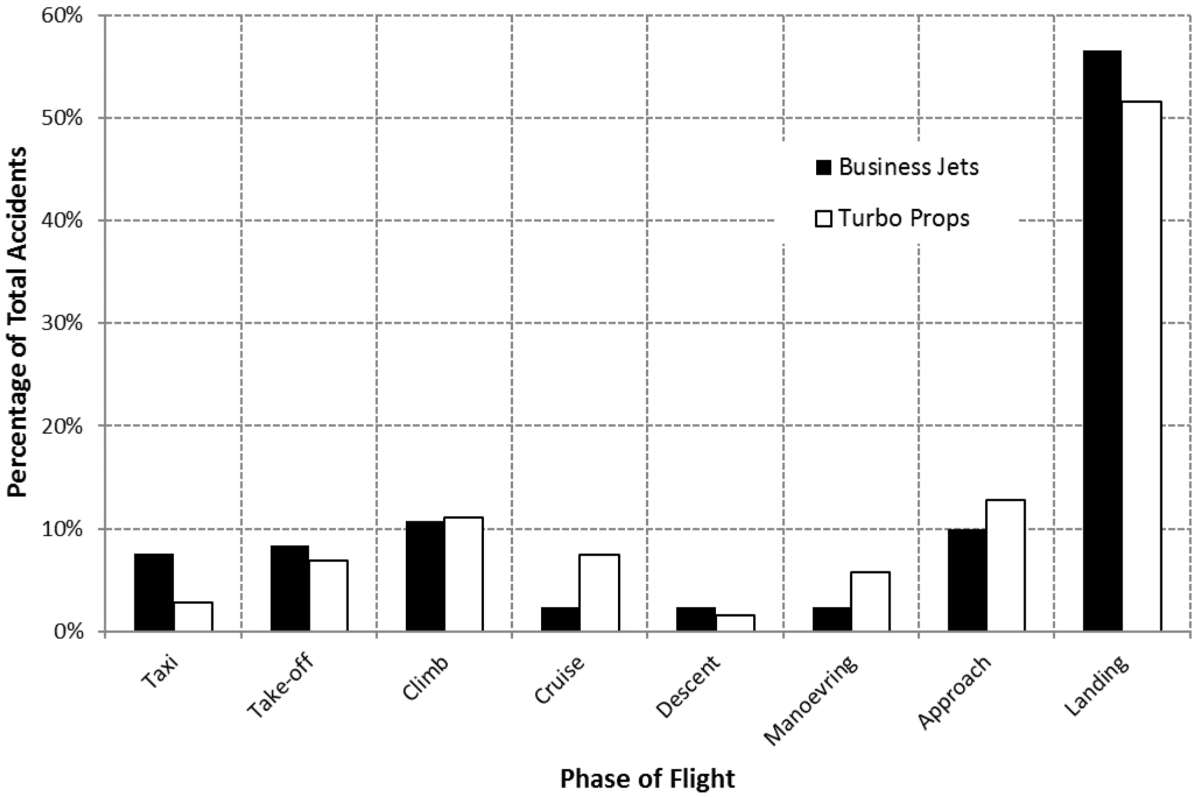

Fig. 1 Business Aviation Accidents for USA from 2009 to 2013 by Phase of Flight - Adapted from [2]

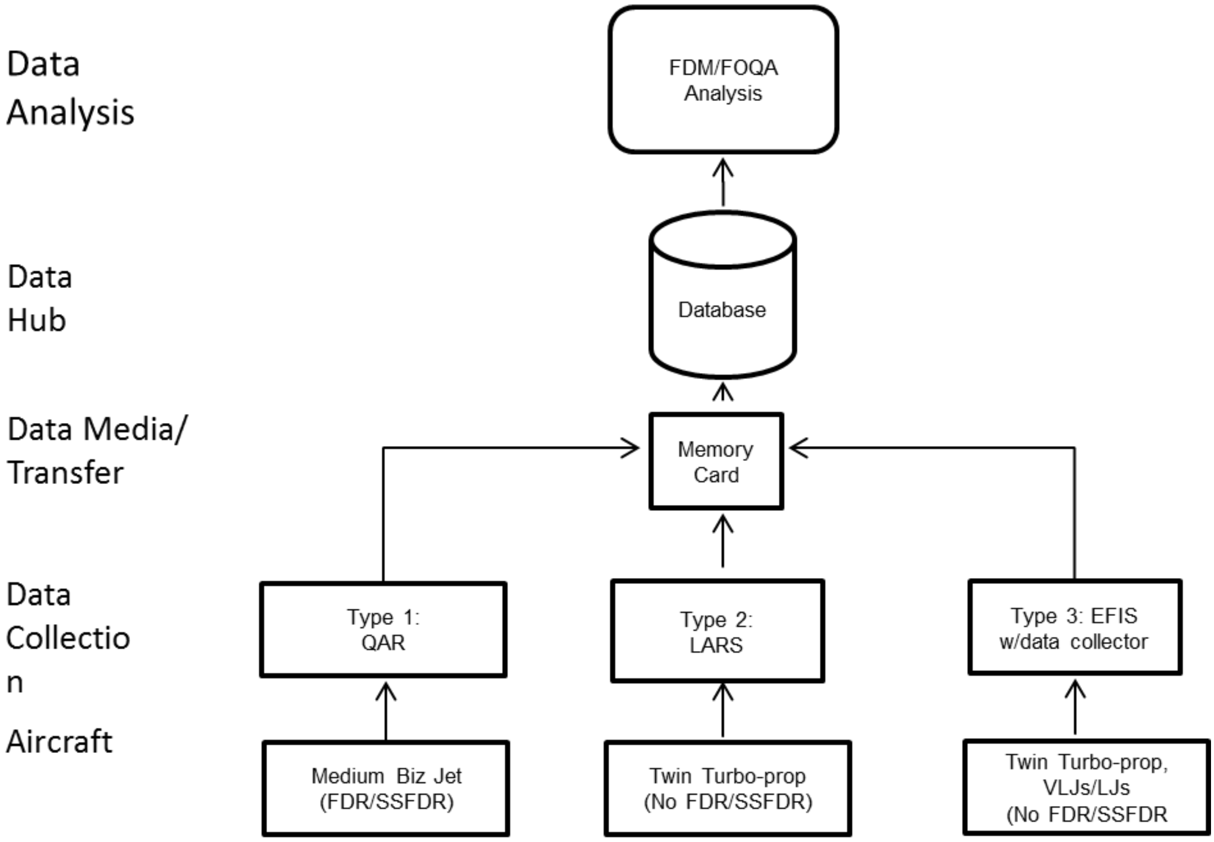

Fig 2 FDM/FOQA/FOQM and Data Recording Device Types – Adapted from [6]

III. Method

Previous studies into the effectiveness of QARs to support FOQA/FDM for business aviation utilised practical flight trials with QARs installed on a limited number of airframes [7]. With each airframe used by different operators in different environments this approach generated different flight data and generated different safety events. This approach was considered impractical for the comparative assessment of the effectiveness of different types of data recording since the number and type of safety events is unpredictable and disparate within an uncontrolled environment. Therefore, simulated flights were proposed and these were to be conducted in a commercial flight simulator to generate consistent flight and safety event data in a controlled environment. The initial intention was to append these evaluation flights to recurrent flight checks for participant pilots on a voluntary basis using additional simulator time incurring additional cost. However, preliminary discussions with the simulator operator, flight instructors and FDM specialists, suggested that routine LPC/OPC check flights might also generate the required data thus avoiding additional time or incurring additional cost. A detailed examination of the LPC/OPC tasks indicated that several safety events were likely to be generated due to the nature of the scenarios and intended pilots' actions. These events included abnormal and emergency procedures such as take-off with simulated engine failure, rejected take-off, TCAS advisory and engine fires etc.

Having established the suitability of simulated flights (LPCs/OPCs), four flights were conducted in a Gulfstream G550 Full Flight Simulator to generate safety events in a controlled environment. Ethical guidelines and procedures were followed and all data was anonymised by the simulator operator. Using the simulator data logging function, 86 flight data parameters were recorded at a frequency of 8 Hz for the duration of all simulated flights. The recorded, simulated flight data was exported in *.CSV file format and then down-sampled as required to emulate 3 different types of data collection devices (QAR, LARS and EFIS) at representative sampling rates using a defined methodology (Fig 3). For the QAR, down-sampled data rates varied from 0.25 to 8 H z depending upon the variable type. For example, 2nd order variables such as (Normal) Acceleration are typically measured at 8 Hz whereas 1st order variables such as Engine Pressure Ratio are typically measured at 0.25 Hz. For the LARS down sampled data rates, all variables were defined at 4 Hz and for the simulated EFIS all data rates were 1 Hz. A full list of parameters and sampling rate for all simulated devices is given in the Appendix.

These data were then converted into required formats for upload into a commercial FOQA/FDM analysis package. FOQA/FDM analysis packages typically accept data defined in Logical Frame Layouts [8]. These layouts are data maps that describe the format used to transcribe data to a recording device. The LFL documents details where each bit of data is stored. Even though standardised by airplanes manufacturers, the LFL may change in response to new regulatory requirements, resulting in different LFLs on airplanes of the same type and also vary with the available onboard systems and databus. Regulations on the parameters to be recorded only relate to the DFDR, however they also impact QAR data since this data is generally a copy of DFDR data [9, 10, 11, 12].

All QAR/DFDR data is stored in digital (binary) format hence analogue data is converted to digital data in binary format (e.g. AoA). The FDAU aggregates this binary data for different parameters in a specific order and then transmits the resultant data to the recorder. The sequence which parameters are aggregated is defined by the data frame, specific to an airplanes type and installed equipment. A data frame describes all the parameters recorded, along with associated data allowing retrieving the binary, and then the original value: the position in the frame, the recording frequency, the resolution, the unit, etc.).

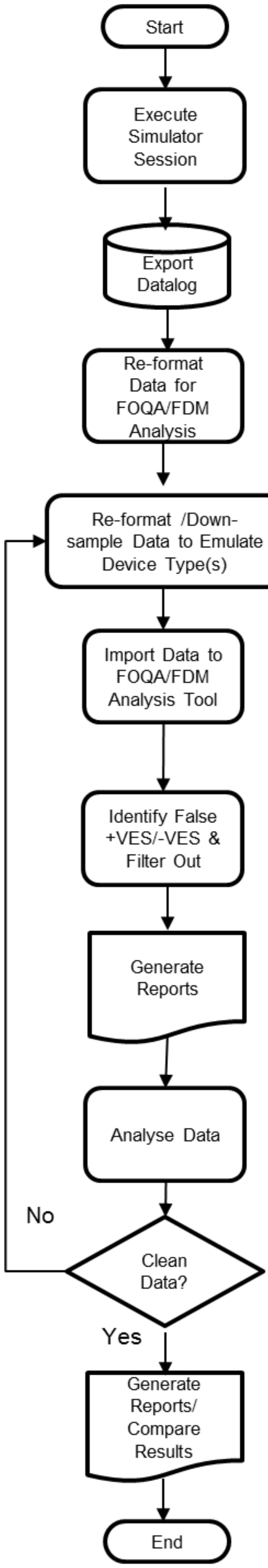

Fig 3 Methodology for Data Extraction & Analysis

Using the LFL definition, the binary data can be decoded from the recorder. The QAR was used as the experiment 'baseline' sampling 86 parameters at 0.25 to 8 Hz, the LARS using GPS/AHRS sampling 16 parameters at 4 Hz and EFIS (with assumed data export facility) sampling 49 parameters at 1 Hz. The simulator data was collected during four separate simulator sessions of 2~4 hours during LPC/OPCs conducted by four different commercial pilots. In accordance with ethical procedures, data was de-identified and not presented or discussed with instructors or pilots. The simulator sessions (LPCs/OPCs) comprised a series of pre-planned exercises including normal and emergency procedures in order to evaluate line/operator proficiency. This provided a means of generating research data without incurring the significant costs of FFS hire with cooperation of the simulator operator. Instructors introduced additional tasks to satisfy the requirements of the LPC/OPC as deemed appropriate. Parts of the LPC/OPC were repeated during the simulator sessions to meet the objectives of the LPC/OPC.

IV. Experimental Results

The commercial FOQA/FDM analysis package included 200+ defined safety events in total across all phase of flight. The number of safety events detected was dependent upon the sensing and recording capability of each device type (Table 1). For example, the 'baseline' QAR (86 parameters) was capable of detecting all events in 6 different categories (as defined by the analysis package) these ranging from accelerations to configurations and warnings. Neither the EFIS (48 parameters) or LARS (16 parameters) were capable of sensing configurations or warnings. The EFIS system with access to pitot/static data was capable of sensing and recording air data.

Table 1, Sensing/Recording Capability by Device Type

	QAR Type 1	**LARS Type 2**	**EFIS Type 3**
No. Parameters	86	16	48
Sampling Rate(s)- Hz	0.25~8	4	1
Accelerations	X	X	X
Attitude/Heading	X	X	X
Flightpath	X	X	X
Air Data	X		X
Configurations	X		
Warnings	X		

For the four given simulated flight scenarios and simulated sensing/recording capabilities for all 3 devices, the preliminary results (Table 2 & Fig 4) show that when compared to the QAR as a 'baseline', the simulated EFIS system detected 58% of all safety events across all flights/phases using 49 parameters sampling at 1 Hz. The simulated LARS detected 23% of safety events across all flights using 16 parameters sampling at 4 Hz during only during the take-off & climb and approach & landing phases of flight.

Table 2, Summary of Number of Events/Types by Phase of Flight & Device

Event Type/Phase	QAR Type 1	LARS Type 2	EFIS Type 3
Acceleration	**1**		**1**
Ground	1		1
Attitude	**34**	**15**	**29**
Air	3		3
Landing & Approach	10	2	13
Take Off & Climb	21	13	13
Configuration	**6**		
Air	1		
Landing & Approach	4		
Take Off & Climb	1		
Flight Path	**28**	**7**	**13**
Air			1
Landing & Approach	28	7	10
Take Off & Climb			2
Speed	**8**		**13**
Ground	1		
Landing & Approach	7		10
Take Off & Climb			3
Warnings	**19**		
Air	1		
Landing & Approach	15		
Take Off & Climb	3		
Grand Total	**96**	**22**	**56**
Using QAR as a 'baseline'	**(100%)**	**(22.9%)**	**(58.3%)**

Table 3, Summary of Number of Events by Phase of Flight & Device

Phase of Flight	QAR Type 1	LARS Type 2	EFIS Type 3
Air	5	0	4
	(100%)	(0%)	(80%)
Ground	2	0	1
	(100%)	(0%)	(50%)
Landing & Approach	64	9	33
	(100%)	(14%)	(52%)
Take Off & Climb	25	13	18
	(100%)	(52%)	(72%)
Grand Total	**96**	**22**	**56**
Using QAR as a 'baseline'	**(100%)**	**(22.9%)**	**(58.3%)**

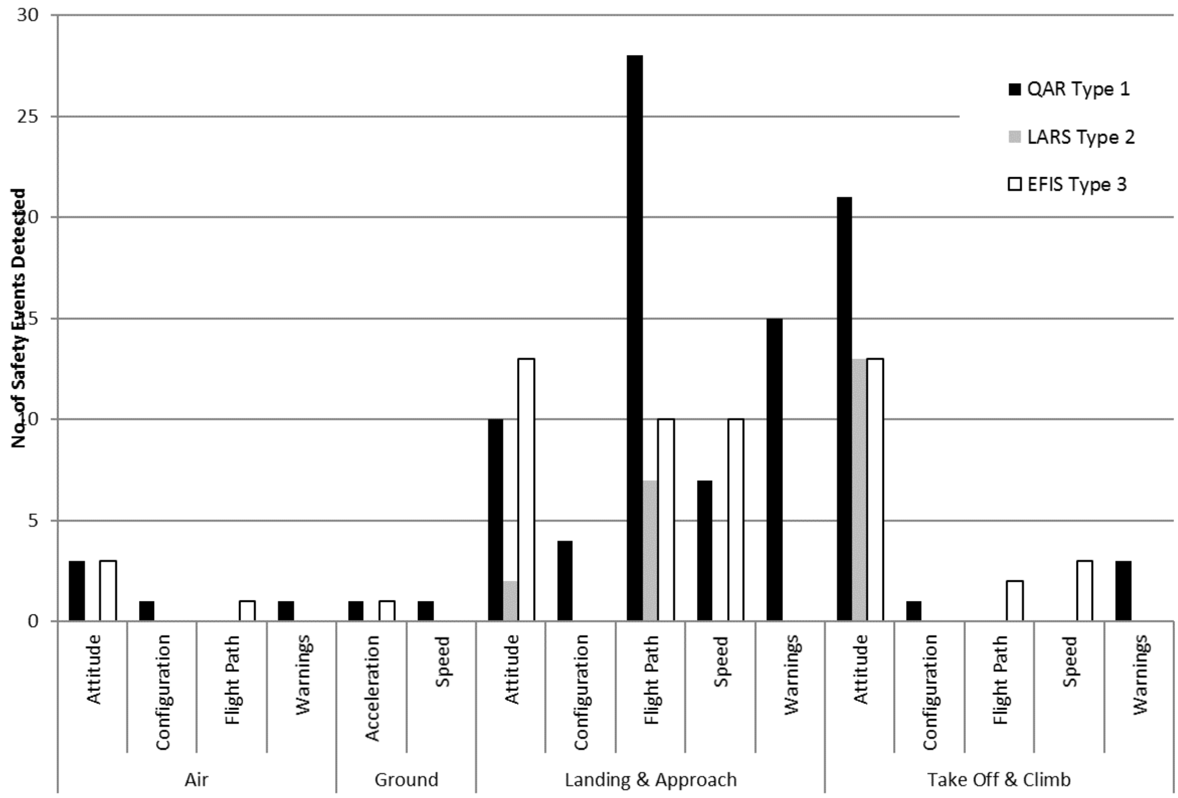

Fig 4 Summary of No. Safety Events Detected by Type & Phase of Flight and Device Type (All Simulated Flights)

V. Discussion of Results

The results show that when compared to the QAR as a 'baseline' (assuming 100% of generated safety events detected) the EFIS system performed well (58.3% of safety events) with the LARS less so (22.9%). The lower detection rate of EFIS systems when compared to QAR was due the lack of configuration and warning parameters combined with the low sampling rate of the device emulated (1 Hz). The lower detection rate of LARSs when compared to QARs was due to the lack of air data (airspeed, pressure height etc.), configuration and warning data. During the analysis of data, it was found that false positive' and 'false negative' events were present.

The 'false positive' events detected were related to airspeed and configuration events and were mainly related to the LARS and EFIS. They were likely triggered by the use of fixed/dummy values of selected parameters such as flap setting and air/ground switch etc. as these data are not sensed/recorded by either of these device types but are required (and expected) by the commercial FOQA/FDM analysis system to identify and confirm flight conditions/phases. In addition, the lack of CAS for LARS resulted in the substitution of CAS with GSPD incurring differences due to the effects of windspeed. False positive events were also generated for the simulator device and QAR device and these were due to discontinuities in the (simulated) flight data. Examiners/instructors frequently re-position the airplanes to perform and/or repeat tasks as part of the LPC/OPC checks and as such flights do not follow the normal sequence of flight phases (e.g. taxi, take-off, climb, cruise, descent etc.). These discontinuities are not normally present in routine FOQA/FDM.

Analysis of the data showed that 'false negative' event types were also present - events expected to be detected by the QAR were missed. Upon investigation it was found that the key parameters pitch, rate of climb/descent, wind speed/direction and stick pusher activated were inadvertently omitted from the emulated QAR definition (Appendix A). These parameters would normally be included in the definition of the QAR LFL and required for complete analysis by a FOQA/FDM system. Pitch is always present, climb or descent rates are either recorded or derived, wind speed/direction are usually recorded but not essential to FDM and stick shaker/pusher are always recorded. The inclusion of these missing parameters where applicable, would increase the number of detected safety events for the devices emulated, therefore the results for emulated QAR devices are likely to have been understated. In addition, the slow sampling rate used for roll angle (2 Hz) compared to pitch angle (4 Hz), may also account for the missing event 'excessive bank on take-off'. Further detailed analysis of the data is desirable.

Notwithstanding these limitations, the preliminary results are encouraging and suggest that EFIS systems with appropriate data parameter set can usefully support a FOQA/FDM programme. Although LARSs are more limited, the identification of safety events in the take-off & climb and approach & landing may assist operators in preventing future accidents in these safety-critical phases of flight. Further, detailed analysis of the safety events data is necessary to draw final conclusions and recommendations for future enhancements of EFIS data capture and use of LARSs.

VI. Conclusions

The study has evaluated 3 different types of data collection devices (QAR, LARS and EFIS) and the number, frequency, precision and accuracy of recorded flight data parameters has been established. Each device type has been successfully emulated using simulated flights generating sufficient detectable safety events for valid comparison.

For the tests and simulated devices using a commercial FOQA/FDM analysis solution it has been shown that the emulated LARSs is capable of detecting up to 22.9% of safety events in all phases of flight combined with 50% of safety events in the take-off & climb but only 14% in the landing and approach (the most safety critical phases of flight (2). The extension of the basic parameter set (16 parameters) by the use of data derived from the basic set and use of supplementary data such as wind speed/direction and terrain etc., may enhance device capabilities and further investigation is recommended.

In contrast, EFIS systems where installed, offer broader capability at no additional cost, detecting at least 58.3% of safety events in ALL phases of flight with 72% in take-off & climb and 52% in landing and approach due to the availability of additional parameters (e.g. air data and real-time weather information). The addition of configuration and warning information to EFIS systems could further enhance capabilities in support of FOQA/FDM programmes for Business Aviation.

In summary, where fitted EFIS systems used for data collection in support of a FOQA/FDM programme for Business Aviation airplanes less than 20 tonnes MTOW may offer several advantages over the LARS solutions, these being lower cost and ability to detect > 50 % of safety events in ALL phases of flight. That said, LARSs enable basic FOQA/FDM capability for data collection for legacy airplanes where EFIS systems are not installed and data is not normally available.

It has been demonstrated that the use of flight simulation and LPC/OPC data (at no cost) can be used as an effective means in the evaluation of COTS technologies in support of a FOQA/FDM programme and this method may be extended to other devices using an existing data set. The method has potential to reduce the time required to complete a manual desktop evaluation of a new airplanes introduced to the fleet and a practical means by which to evaluate the newly defined LFLs using simulated flight data representative of that which will be present in normal and abnormal flight operations.

Appendix

Parameters/Sampling Frequency by Device Type

PARAMETER/SAMPLING FREQ. (Hz)	Simulator	QAR Type 1	LARS Type 2	EFIS Type 3	Units	Notes
Timestamp	8	8	4	1	sec	
Calibrated_Airspeed	8	1		1	knot	
Groundspeed	8	1	4	1	knot	
Pressure_Altitude	8	1	4*	1	foot	LARS = GPS Altitude
AAL	8	1			foot	
Runway_Length	8				foot	
Radio_Altitude	8	2			foot	
Magnetic_Heading	8	1	4	1	deg	
Indicated_Mach_Number	8	1			Mach	
Pitch_Angle	8	4	4	1	deg	
Roll_Angle	8	2	4	1	deg	
Yaw_Angle	8	1	4		deg	
Outside_Air_Temperature	8	1		1	degC	
Gear	8	1			%	
Flap_Lever	8	1			%	
Flap	8	1			%	
Spoiler_Lever	8	1			%	
Spoiler	8	1			%	
Spoiler_2	8	1			%	
Spoiler_3	8	1			%	
Spoiler_4	8	1			%	
Spoiler_5	8	1			%	
Spoiler_6	8	1			%	
Spoiler_7	8	1			%	
Spoiler_8	8	1			%	
Angle_of_Attack	8	1			deg	
Pitch_Rate	8	4	4		deg/s	
Roll_Rate	8	2	4		deg/s	
Yaw_Rate	8	1	4		deg/s	
Weight	8	1			lb	
Normal_Acceleration	8	8	4	1	ft/s^2	
Longitudinal_Acceleration	8	2	4		ft/s^2	
Lateral_Acceleration	8	2	4	1	ft/s^2	
Engine_#1_Pressure_Ratio	8	0.25		1	%	
Engine_#2_Pressure_Ratio	8	0.25		1	%	
Reference_Speed	8	1			knot	
Reference_Speed_With_Current_Flap	8	1			knot	

Air_Ground	8	2				
EGPWS	8	1				
Stick_Shaker	8	1				
Stick_Pusher	8					Missing from QAR LFL
Master_Warning	8	1				
TCAS_Warning_Vertical_Speed	8	1		1		
TCAS_Warning_Climb_Climb	8	1		1		
TCAS_Warning_Climb_Climb_Now	8	1		1		
TCAS_Warning_Climb_Crossing_Climb	8	1		1		
TCAS_Warning_Clear_Conflict	8	1		1		
TCAS_Warning_Descend_Crossing_Descend	8	1		1		
TCAS_Warning_Descend_Descend	8	1		1		
TCAS_Warning_Descend_Descend_Now	8	1		1		
TCAS_Warning_Increase_Climb	8	1		1		
TCAS_Warning_Increase_Descent	8	1		1		
TCAS_Warning_Monitor_Vertical_Speed	8	1		1		
TCAS_Warning_Maintain_Vertical_Speed_Cros	8	1		1		
TCAS_Warning_Maintain_Vertical_Speed_Main	8	1		1		
TCAS_Warning_System_Test_Fail	8	1		1		
TCAS_Warning_System_Test_OK	8	1		1		
TCAS_Warning_Test	8	1		1		
TCAS_Warning_Traffic_Traffic	8	1		1		
TCAS_Warning_Test_Complete	8	1		1		
TCAS_Warning_Test_Track	8	1		1		
TCAS_Warning_Test_Lost	8	1		1		
TCAS_Warning_Test_Dropped	8	1		1		
Latitude	8	1	4	1	deg	
Longitude	8	1	4	1	deg	
Glideslope	8	1			dot	
Localiser	8	1			dot	
GPS_Altitude	8		4		foot	Missing from EFIS LFL
Vertical_Speed	8		4	1	ft/min	
Altitude_Above_Mean_Sea_Level	8		4*	1	foot	LARS = GPS Altitude
Track	8			1	deg	
Track_for_Test_Output	8			1	deg	
Engine_#1_Fuel_Flow	8			1		Missing from QAR LFL
Engine_#2_Fuel_Flow	8			1		Missing from

						QAR LFL
Engine_#1_Oil_Temperature	8			1	degC	
Engine_#2_Oil_Temperature	8			1	degC	
Engine_#1_Oil_Pressure	8			1	psi	
Engine_#2_Oil_Pressure	8			1	psi	
True Airspeed	8			1	knot	
Course	8			1	deg	
Windspeed	8			1	knot	Missing from QAR LFL
Wind_Direction	8			1	deg	Missing from QAR LFL
Elevator_Position	8				deg	
Port_Aileron	8				deg	
Starboard_Aileron	8				deg	
Rudder_Deflection	8				deg	
Total Number of Parameters	**86**	**65**	**16**	**49**		

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